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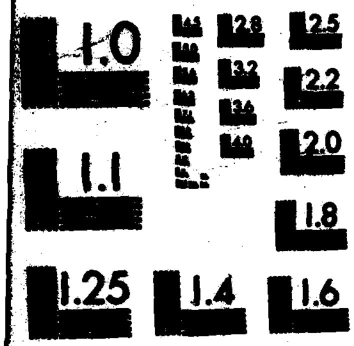

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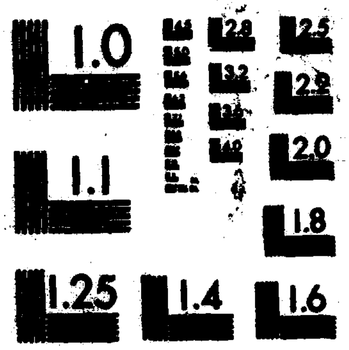

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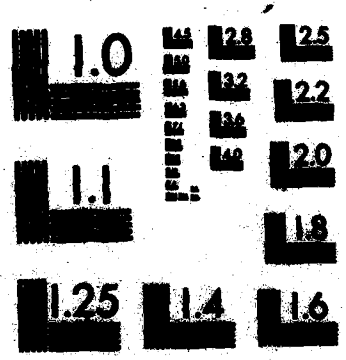

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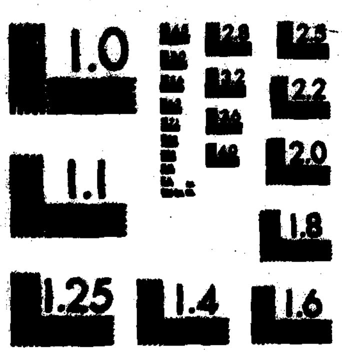

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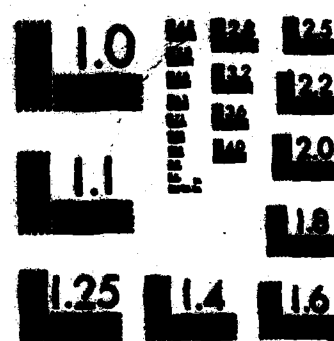

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We describe the use of a ballistic pendulum array to measure the momentum of a laser-produced plasma. An insitu calibration method is described and the pendulum results are compared to measurements made with other diagnostics.

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BALLISTIC PENDULA FOR MEASURING THE MOMENTUM OF A LASER-PRODUCED PLASMA

INTRODUCTION

In laser-driven inertial confinement fusion the momentum of a laser-produced plasma creates the pressure necessary to implode a DT containing pellet. To measure such momentum (pressure) we utilize a number of instruments and techniques [1,2] among them an array of ballistic pendula [3]. These devices were initially chosen because they measure the plasma momentum directly and because they are, in principle, simple and easy to understand. Pendula have been used in laser-produced plasma experiments for many years [4-8]. However, we found that these pendulum measurements are not trivial, and that results of many experiments may be misleading. The reason is this: Pendula are time and space integrating devices that cannot distinguish between momentum generated during and after the laser pulse, or between momentum generated inside and outside the laser-target interaction area. Since momentum is proportional to the square root of mass multiplied by energy, a small amount of energy may heat a large extraneous mass and produce a large but irrelevant momentum. And, unfortunately, in typical laser-plasma experiments there are often extraneous mass sources. For example, extraneous mass is present in unirradiated regions of the target foil or in the stalks used to support disk or pellet targets. Mechanisms that may transport small amounts of energy outside the interaction area include: radiation from the plasma plume, return currents in stalks or supports [9], thermal conduction of energy through the laser focal-spot periphery [10,11], or energy conduction via fast electrons [12].

Another source of erroneous momentum measurements could be the material which is "reflected" or photoionized off a pendulum surface, or sputtered from it by the ablation plasma [13]. Generally, the sputtered or reflected material contains only a small fraction of the incident plasma energy [3,14], but, as we will show, it can contain as much momentum as the incident plasma.

It is important, therefore, to verify that the above mentioned mechanisms are not important in particular experiments, or to take proper account of them. To our knowledge this has not been done in the past. In this paper we describe an array of ballistic pendula that has been calibrated in situ to account for momentum contributions due to sputtering, reflection of incident plasma, or photoionization of the pendulum surface. Our experiments utilize finite disk targets supported by thin fibers so that the amount of extraneous mass outside the laser-target interaction area is minimized. As part of the calibration we verified that the pendulum array obeys basic physical laws such as the conservation of momentum and mass. These tests are an independent check on the absolute calibration of the array. Finally, the pendulum results were cross-checked with the results of other diagnostics.

DESIGN OF THE EXPERIMENT

In our experiments we use planar targets irradiated by a single laser beam. Since the targets are planar, both the plasma momentum (pressure) and the resulting motion of the target can be measured conveniently. The Nd-laser pulse, which has a wavelength of 1.05 μm and a duration of 4 nsec, irradiates the target at 1×10^{11} to 4×10^{13} W/cm^2. In this regime there are few fast electrons or fast ions. In fact, the plasma ions exhibit a narrow, single peaked velocity distribution so that the use of temporally integrating ballistic pendula is meaningful. Likewise, time-of-flight ion collectors work well under these conditions. Our measurements scan a fairly broad range of parameters. For example, plasma ion or target debris velocities range from 10 to 600 km/sec with an equivalent momentum of

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10^{-17} to 10^{-15} dyne-sec/ion. Pressures on the target surface range from 0.1 to 6 Mbar and target momenta from 2 to 50 dyne-sec.

Figure 1 shows the experimental arrangement. The laser beam is focused onto a 300 to 1200 μm diameter spot on the target surface by a 1.2 meter aspheric lens. Temporal and spatial profiles as well as the energy of the beam are recorded on each shot. The target itself is surrounded by an array of six ballistic pendula; three on the laser side, and three on the rear cooler side of the target. Specifically, the pendula are about 20 cm from the target at $-19°$, $-33°$, $-50°$, $145°$, $162°$, and $235°$ to the target normal. A typical pendulum subtends about 0.03 sr solid angle. Coplanar with the pendula is an array of 8 time-of-flight ion collectors and an array of 9 plasma calorimeters. Together, these detectors directly measure the angular distribution of the ablation plasma and target debris momentum $p(\theta)$, velocity $u(\theta)$, and energy $e(\theta)$.

Using these three diagnostic arrays together, we can cross-check the results of the pendulum array. For example, by integrating $p^2(\theta)/2e(\theta)$ over all solid angle we can calculate the total mass of the plasma and the target debris—which should be equal to the actual target mass if the pendulum measurements are correct. Similarly, it is possible to compare the directly measured ablation plasma momentum with that inferred by integrating $2e(\theta)/u(\theta)$. The results of such comparisons are shown in the next section.

A typical pendulum consists of a rectangular collecting surface which is suspended by nylon threads or, in some cases, by a rigid plastic structure pivoted on a razor-sharp edge. In either case the friction at the pivot point is minimal and the pendulum is effectively undamped. The collecting surfaces are made of either brass or mylar and are 2.5 × 4 cm in dimension. The pendulum's angular velocity is measured with a 200 to 1000 turn pickup coil[6] which is attached on one side to the collecting surface while its other side moves freely between the poles of a 3 KG magnet. The voltage induced in the pickup coil by the pendulum motion is amplified 100 times and then filtered with a low-pass (10 Hz), 6-pole, Butterworth filter (Fig. 2). Such filtering greatly reduces any voltage induced by building vibrations or vacuum pumps. A remotely controlled solid state switch is used to damp out pendulum motion prior to a shot.

The momentum M of plasma striking a pendulum and the voltage induced in the pickup coil are related by Faraday's and Newton's laws thru the relation

$$M = 1.2 \times 10^6 \beta \frac{md}{lBran\nu^2} V_{p-p}(\mathrm{mV}) \qquad \text{(Gaussian units)}$$

where m is the pendulum mass, d is the pivot to center-of-mass distance, n is the number of pickup coil turns, B is the magnetic field strength, r is the pivot to magnet gap distance, a is the length of the coil which is in the magnetic field, l is the pivot to collecting surface distance, ν is the pendulum resonant frequency, and V_{p-p} is the peak-to-peak induced voltage in millivolts. The parameter β is the correction factor needed to account for possible pendulum surface photoionization, sputtering, or reflection of plasma from the pendulum surface: if all the plasma "sticks" to the pendulum, for example, then $\beta = 1$. Since all of the parameters in the above equation, except β, are easily measured the pendulum is very easy to bench-calibrate. We double-checked the pendulum response by striking it with a soft wax pellet of known momentum. Not surprisingly, the two calibration methods agreed to within 8%. The sensitivity of our pendula varies from 7 to 34 mV/dyne-sec, depending on the pendulum dimensions and number of coil turns.

As we already mentioned, photoionization, the elastic or inelastic nature of the plasma-pendulum collision, or sputtering can affect the in-situ calibration of the pendulum. To measure these effects we built a double-pendulum device (Fig. 3). This device consists of two pendula facing each other which

are enclosed by an aluminum shield containing a small hole. Plasma which enters through the hole in the shield strikes the pendulum surface that is being calibrated. Any material reflected, sputtered, or photoionized from this surface is detected by the second pendulum which is built in the shape of a rectangular cavity so that it can catch most of this material. To determine β we assume that either any secondary reflection or sputtering from the rectangular cavity is negligible, or that ions reflected or sputtered off one part of the cavity deposit their momentum within another part of the cavity,[15] thereby not adding additional momentum to the system. With these assumptions $\beta = 1/[1 - M_R/M_C]$ where M_R and M_C are the momenta of the rectangular cavity pendulum and the pendulum being calibrated respectively.

RESULTS

Using the double pendulum described in the last section we determined that $\beta = 2.4$ with a standard deviation of 0.6 (Table I).

We noted that the β of brass collecting surfaces tended to be larger and have more scatter than that of mylar surfaces. However, the differences were within the experiment error. Consequently, the value of 2.4 is utilized for both types of collecting surface.

Having thus calibrated the response of ballistic pendula exposed to the plasma, we verified also that the plasma and target debris momenta balance. The result of these measurements for various diameter and thickness disk targets, and irradiances from 5×10^{11} W/cm^2 to 3×10^{13} W/cm^2 are shown in Fig. 4. In making this measurement we assumed that the factor β determined for pendula exposed to the target debris is the same for pendula exposed to the plasma. The good momentum balance shown in Fig. 4 indicates that the pendulum array samples the plasma momentum accurately.

As we argued at the outset of this paper, mass originating outside the focal-spot could be the source of much irrelevant momentum complicating the interpretation of pendulum measurements. The extent of such complications is demonstrated in the following experiment: we measured the target debris and plasma momenta from 30 μm thick, wide, CH foils as a function of laser spot size, which was varied by aperturing the incident laser beam. We found that as the focal-spot size was varied (at constant irradiance) the target debris momentum per unit area remained constant to within $\pm 25\%$—a scatter consistent with shot-to-shot variation and uncertainties in the laser-target interaction area as the focal-spot size is changed. However, the plasma momentum per unit area varied dramatically. This can be seen in Fig. 5 which shows that the plasma and target debris momenta are about equal for small focal-spot sizes but differ by a factor of 7 for large focal-spot sizes. This surprising result may be explained if we assume that a portion of the energy within the focal-spot heats surface material outside the focal-spot thereby creating extraneous momentum measured by the plasma pendula. However, because this energy is low, it does not create sufficient pressure to accelerate the region outside the focal-spot toward the target debris pendula. We suggest radiation from the plasma plume as a possible source of this energy.

To avoid the above mentioned complications we use disk targets, supported by thin fibers, whenever making measurements with pendula. Disk targets have an additional advantage that the laser target interaction area is determined by target geometry so that the absorbed irradiance and momentum per unit area are well known.

A comparison of plasma momentum measured with ballistic pendula with that inferred from ion calorimeters and time-of-flight ion collectors is shown in Table I. The two measurements agree to within 10%.

Finally, using momenta measured with pendula and energy measured with minicalorimeters we determined the ratio of the calculated disk target mass $\int [p^2(\theta)/2e(\theta)]\, 2\pi \sin\theta \, d\theta$ to the actual target

mass. This comparison is sensitive to the accuracy of the in-situ pendulum calibration since the calculated mass is proportional to the square of momentum. As Table I shows the calculated and actual target masses agree. Had we set $\beta = 1$, i.e. used the bench calibration for the pendulum, the calculated mass would have been six times as large as the actual mass.

CONCLUSIONS

We have described a pendulum array that has been used to measure momentum of plasma from laser-irradiated disk targets. The pendula were calibrated in-situ and a mass accounting was done to verify the calibration. *The pendulum measurements were also compared to the results from other ablation plasma diagnostics.*

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15. We estimate that if particles of momentum M_o enter the pendulum cavity so that: (1) the distribution of momentum in the cavity is uniform, (2) each cavity surface scatters all incident momentum uniformly into all solid angles, and (3) no multiple scattering occurs, then the fraction of M_o that escapes the cavity contributing to the pendulum motion is about 0.2 M_o. This estimate models momentum scattered off a pendulum surface by an equivalent momentum emanating from a point source at the surface center.

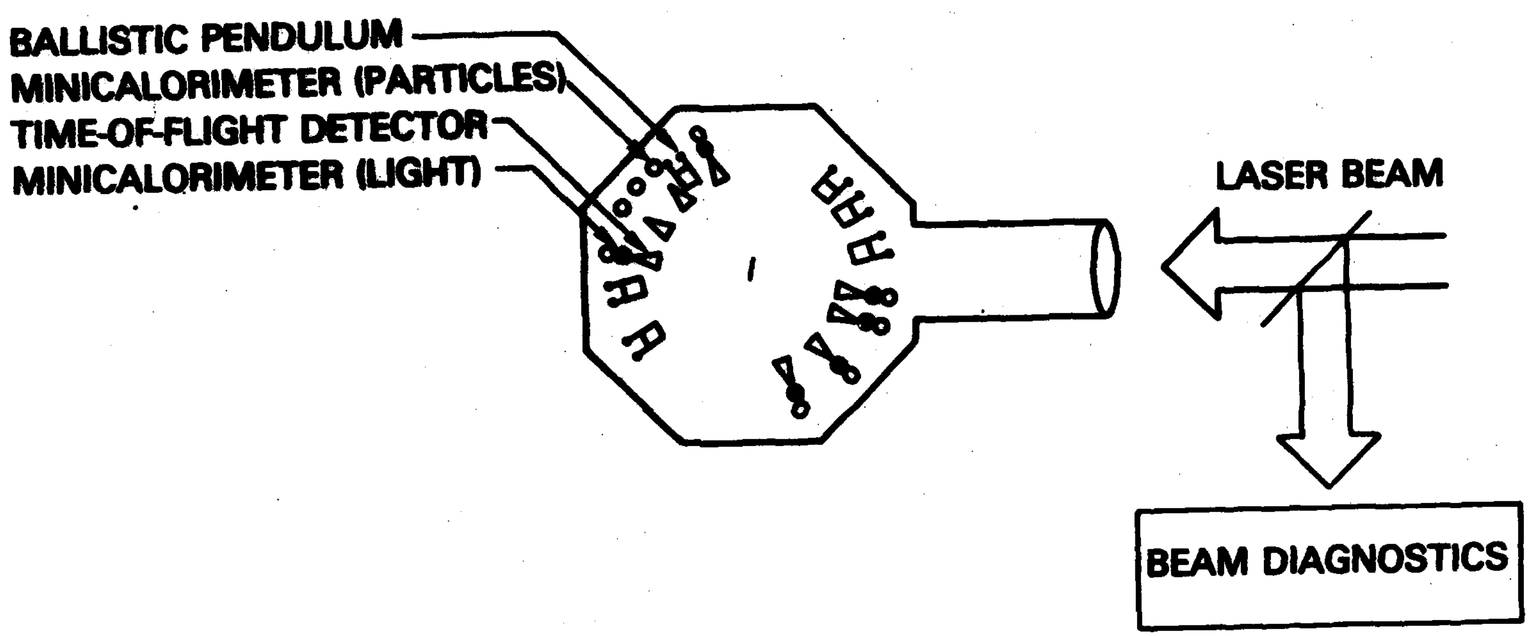

Fig. 1 — Arrangement of experiment

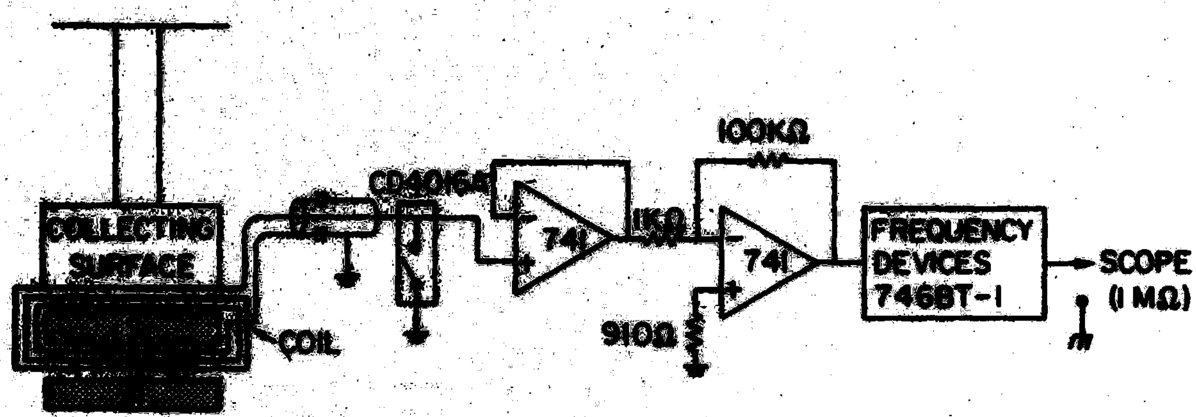

Fig. 2 — Schematic of a pendulum and its electronics

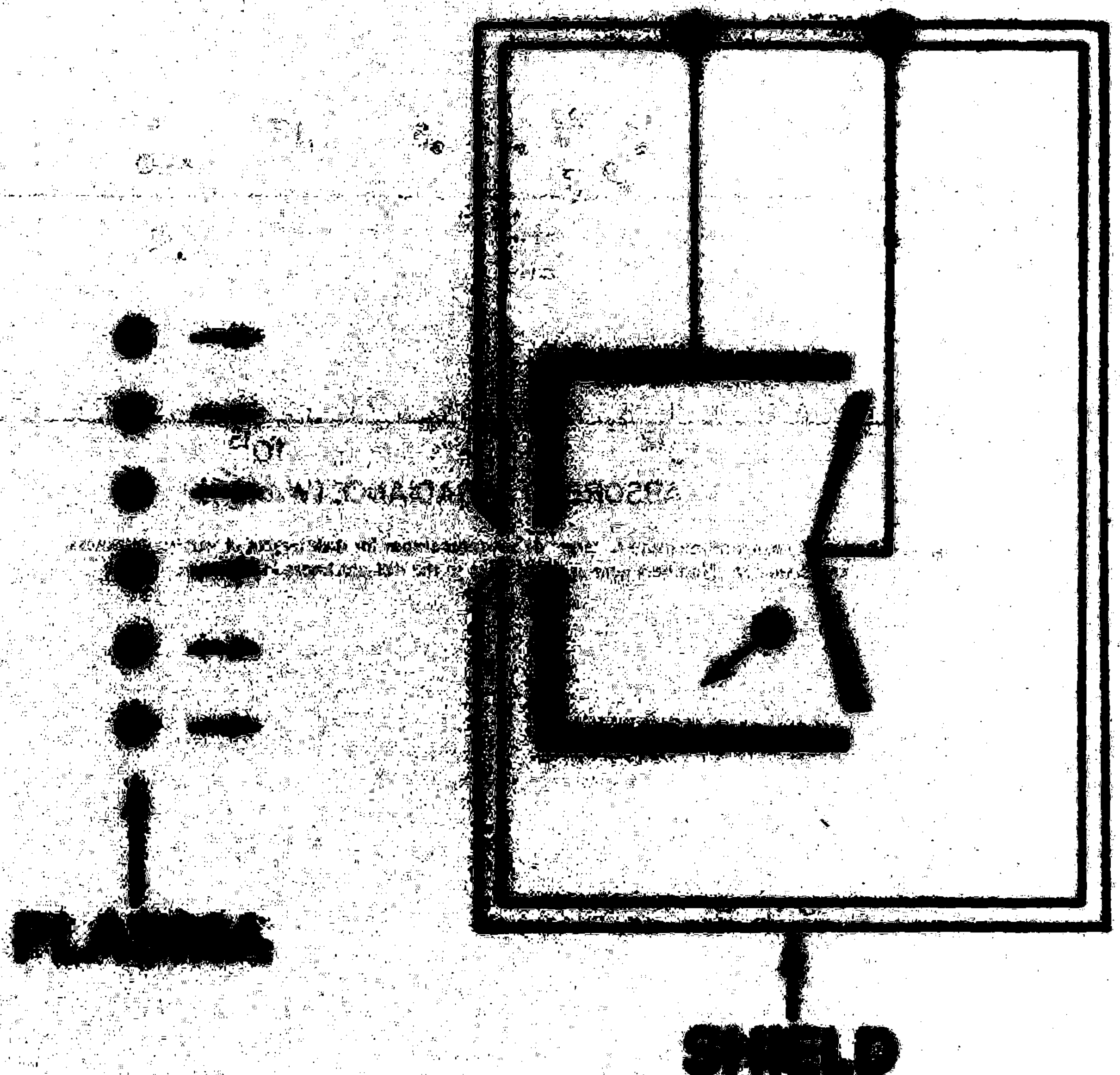

Fig. 3 — Schematic of a double-pendulum

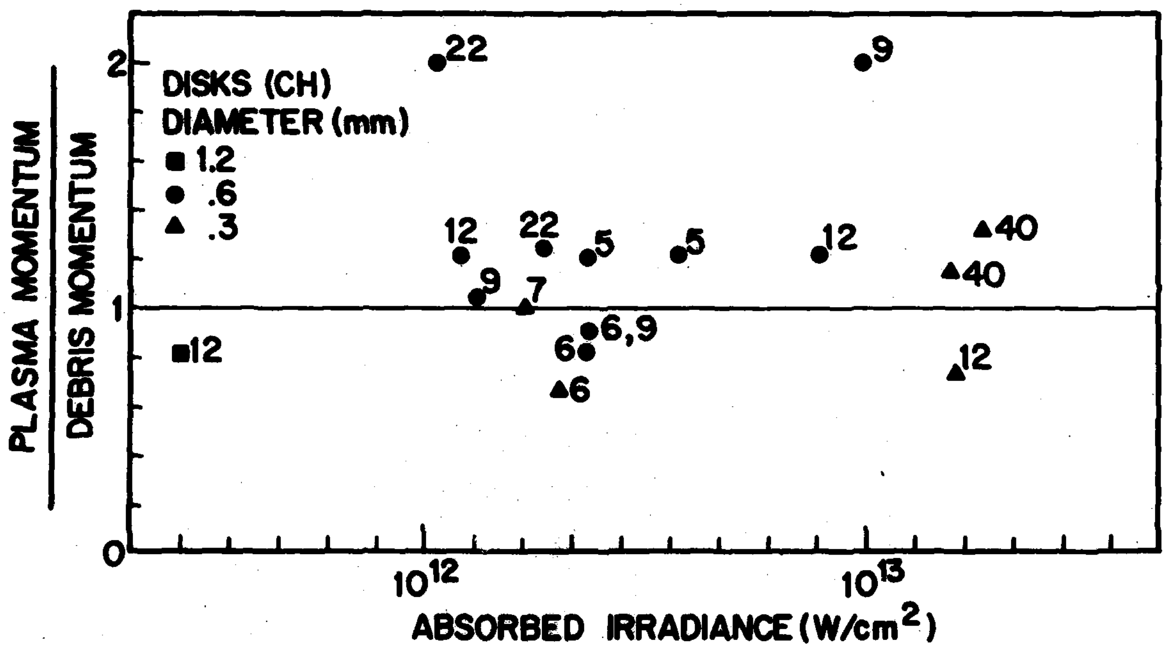

Fig. 4 — Ratios of plasma momentum to target debris momentum for disk targets of varying thickness and diameter. Numbers near symbols refer to the disk thickness in microns.

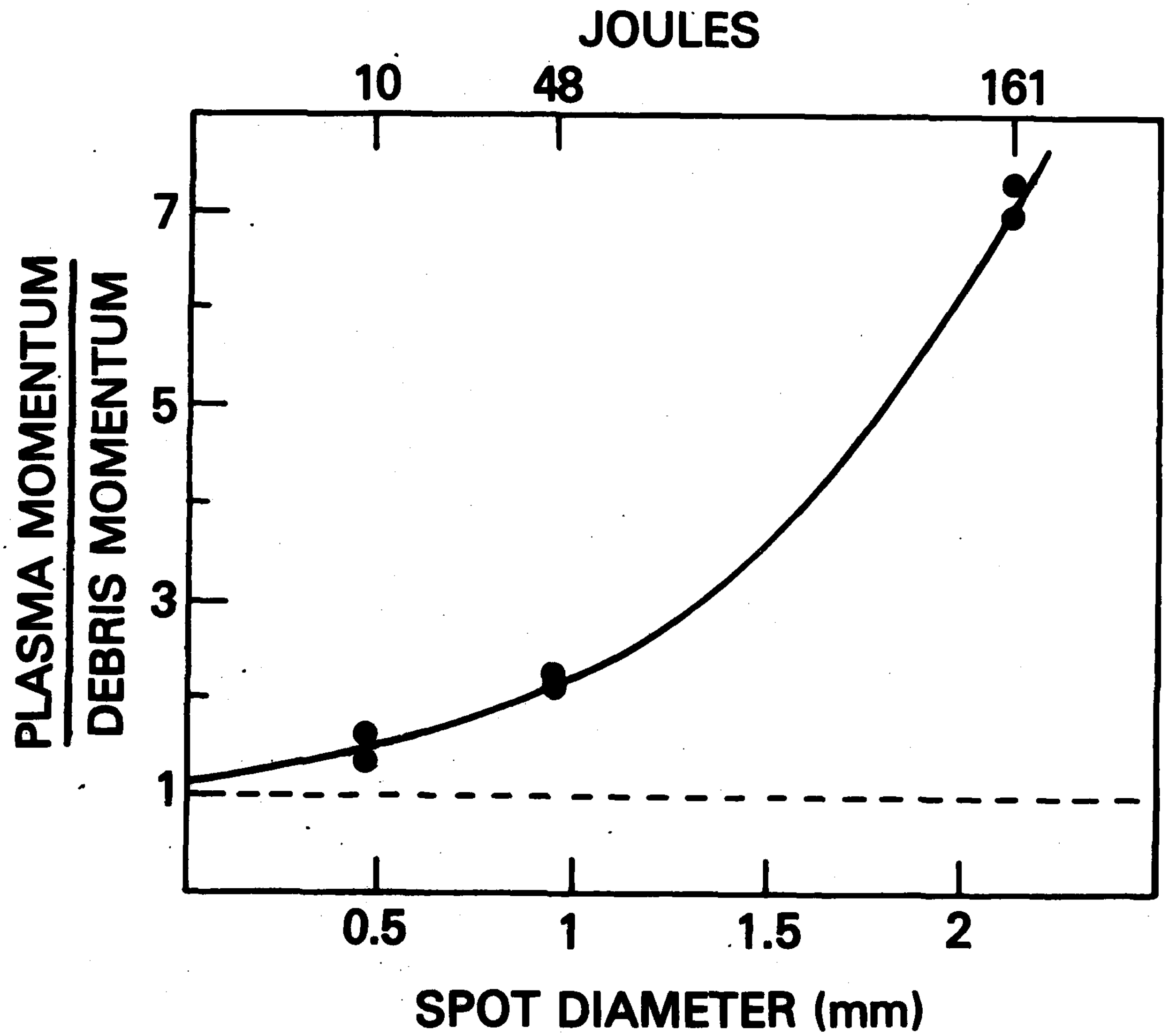

Fig. 5 — Ratio of plasma momentum to target debris momentum as a function of laser-spot diameter. The target is a 30 μm thick CH foil irradiated at 1×10^{12} W/cm^2.

Table I

Results of the pendulum calibration. Top row: Calibration coefficient inferred from double pendulum measurements. Middle row: Ratios of mass inferred from pendula to disk target mass. Bottom row: Ratios of momentum measured with pendulum array to momentum inferred from calorimeter (energy) and ion-collector (velocity) measurements.

	The Mean and the Standard Deviation
Calibration Coefficient	2.4 ± 0.6
<u>Inferred Mass</u> Disk Mass	1.0 ± 0.5
<u>Momentum from Pendula</u> Momentum from cals. and ion collectors	1.1 ± 0.2